# Submesoscale Routes to Lateral Mixing in the Ocean

Amala Mahadevan
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone: (508) 289 3440    fax (508) 457 2181    email: amala@whoi.edu

Grant Number: N00014-12-1-0101

Amit Tandon
Physics Department, UMass Dartmouth
285 Old Westport Rd
North Dartmouth MA 02747
Phone: (508) 999-8357    fax: (508) 999-9115    email: atandon@umassd.edu

Grant Number: N00014-09-1-0196

## LONG-TERM GOALS

To determine whether lateral mixing at O(1-10 km) scales is due to a balanced or unbalanced downscale cascade from the mesoscale, or due to local vertical mixing by internal waves and surface forcing.

## OBJECTIVES

Our work is testing hypothesis 3 of the white paper "Scalable Lateral Mixing and Coherent Turbulence": Non-quasigeostrophic, submesoscale instabilities feed a forward cascade of energy, scalar and Ertel PV variance, which enhances both isopycnal and diapycnal mixing. Related hypotheses are that submesoscale variability is associated with coherent structures and anisotropic mixing. Further, submesoscale processes are inherently vertical, as well as horizontal, and submesoscale processes facilitate cross-front exchange.

## APPROACH

Our approach is to run a number of process studies using a three-dimensional non-hydrostatic Process Study Ocean Model (PSOM, *Mahadevan, 2006; Mahadevan and Tandon, 2006*). The typical model resolution for resolving submesoscales is about 1 km in the horizontal. We have examined processes in domains approximately 100 km x 200 km and 100 km x 500 km.

## WORK COMPLETED

This work benefited from collaborations with Takeyoshi Nagai (TUMSAT, Japan), Eric Kunze, Eric D'Asaro and Craig Lee (all at U.Washington and participants of the LATMIX DRI), and the

| Report Documentation Page | | *Form Approved*<br>*OMB No. 0704-0188* |
|---|---|---|

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

| 1. REPORT DATE<br>**30 SEP 2012** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2012 to 00-00-2012** |
|---|---|---|
| 4. TITLE AND SUBTITLE<br>**Submesoscale Routes to Lateral Mixing in the Ocean** | | 5a. CONTRACT NUMBER |
| | | 5b. GRANT NUMBER |
| | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | 5d. PROJECT NUMBER |
| | | 5e. TASK NUMBER |
| | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Wood Hole Oceanographic Institution,Woods Hole,MA,02543** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **5** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

participation of Ph.D. student Sonaljit Mukherjee (UMassD) and postdoctoral associate, Sanjiv Ramachandran (UMassD).

A modeling study of restratification by mixed layer eddies was undertaken using parameters from the subpolar North Atlantic to understand the role of surface buoyancy fluxes (cooling) in inhibiting restratification. A scaling estimate was derived for the negative buoyancy flux (cooling rate) that prevents restratifiction by mixed layer eddies, much like the effect of downfront winds described in *Mahadevan, Tandon and Ferrari (2010).* The relationship was tested against observations from the North Atlantic during the initiation of the spring phytoplankton bloom (*Mahadevan et al., 2012*).

Two approaches were implemented and tested (by S. Ramachandran and S. Mukherjee, UMassD) for inclusion of appropriate subgrid lateral diffusivities in our model runs of submesoscale frontal dynamics: (i) A Smagorinsky closure scheme for anisotropic grids that models the horizontal subgrid diffusion (Fig. 1), and (ii) constant lateral diffusivity of momentum and tracers with varying vertical diffusivity modeled by a k-$\varepsilon$ closure scheme (Fig. 2).

A modeling study was undertaken to explain observations of banded ageostrophic shear and enhanced dissipation in the Kuroshio front. The Process Study Ocean Model (PSOM) was initialized with observed cross frontal sections. The model was used to quantify the flux of energy from the geostrophically balanced flow into the the internal wave field (Fig. 3) and diagnose the mechanism of internal wave radiation.

Observational data from the 2011 LatMix field experiment is being used to initialize model runs to study the generation of variance in tracer (spice) along isopycal surfaces.

**RESULTS**

The application of the surface-forced model runs to the formation of the North Atlantic bloom resulted in a manuscript published in Science (*Mahadevan et al., 2012*). The study used observations (from an NSF-funded study) and modeling (described here) to show that mixed layer eddies arising from the baroclinic instability of lateral density gradients in the mixed layer can generate stratification prior to the onset of solar warming in the Spring.

A Smagorinsky-type closure for horizontal mixing realizes the theoretically expected rates of energy converstion from potential to kinetic energy. Horizontal diffusivities of magnitude ~ 5 m$^2$/s or larger (used on a 1 km x 1 km grid) tend to be overly dissipative (Fig 1).
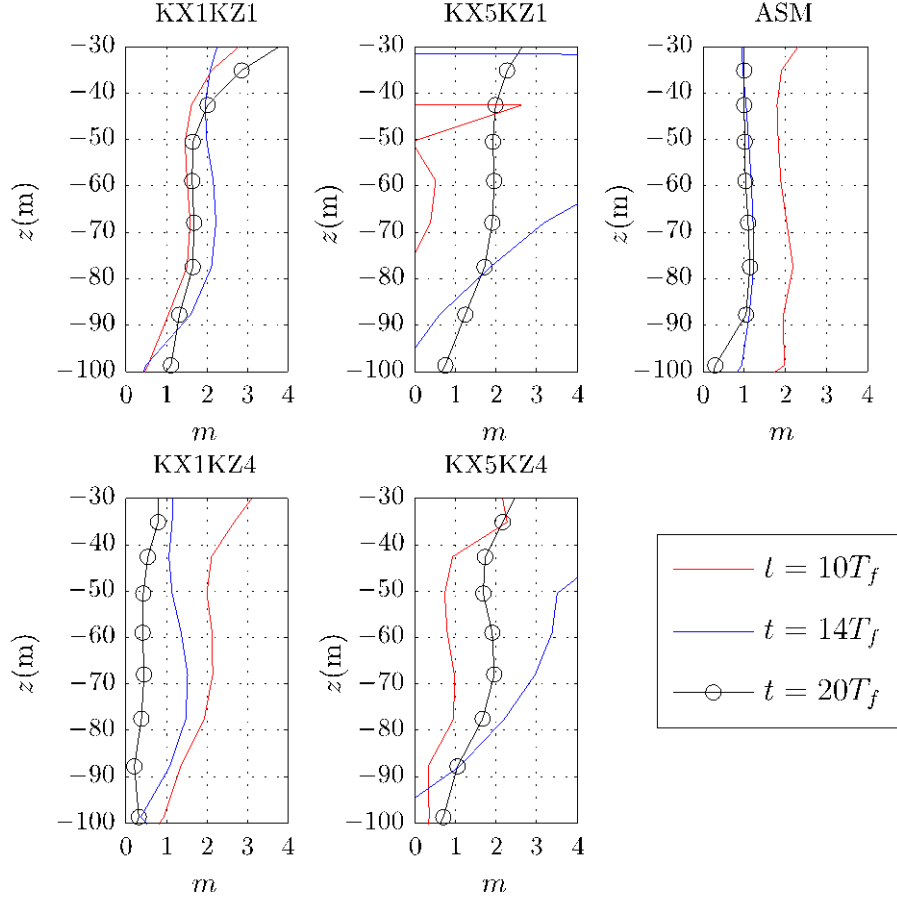
*Figure 1: The comparison of APE extraction for the Anisotropc Smagorinsky Scheme (ASM) vs. those with constant coeffients. KX1KZ1 corresponds to horizontal diffucivity of 1m²/s and vertical diffucivity of 10⁻⁵m²/s. Vertical profiles of m, the ratio of isopycnal slope to ratio of zonally averaged vertical to horizontal buoyancy gradients is shown at three different times in the simulation. For the most efficient APE extraction, this ratio should be 2 (Eady 1949). For the ASM, the ratio is 2 at early times. As the eddies begin to spin down, the mixing is mostly along isoycnals and the ratio is close to 1. The circles on the black curve indicate the vertical grid levels. The APE extraction is not as efficient with constant coefficients as with ASM.*

Lower horizontal diffusivity can be used when coupled with an appropriate vertical mixing scheme using k-ε models in GOTM as sub-grid closures for PSOM. An example of enhanced dissipation near fronts with such a closeure is shown in Figure 2.

Through meandering and the loss of balance, we find that a strong front transfers energy from the balanced state (geostrophic flow) to near-inertial internal waves (NIW) in the vicinity of the front (Figure 3). In our model simulations, the NIW energy is not transported large distances, but is dissipated near the front. This mechanism could make a significant contribution to the sink of energy from the large-scale flow and is important in that it can occur in the ocean interior.
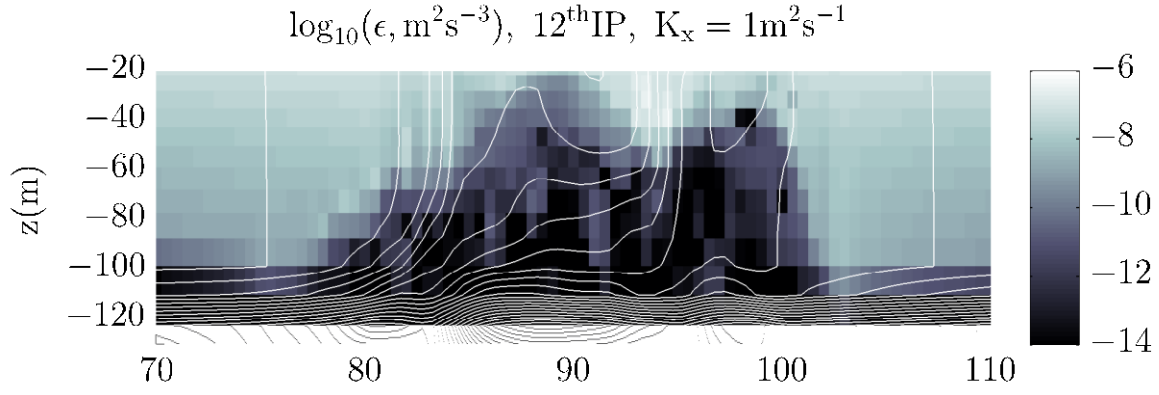
$\log_{10}(\epsilon, \mathrm{m^2 s^{-3}}), \ 12^{\mathrm{th}}\mathrm{IP}, \ K_x = 1\mathrm{m^2 s^{-1}}$

*Figure 2: Dissipation as modeled by coupled PSOM-k-ε GOTM model for a frontal simulation. The k-ε n model is inspired by Venayagamoorthy and Stretch (2010). While enhanced dissipation values are seen near the submesoscale eddy structures, the dissipation decreases to background values in the restratified region.*
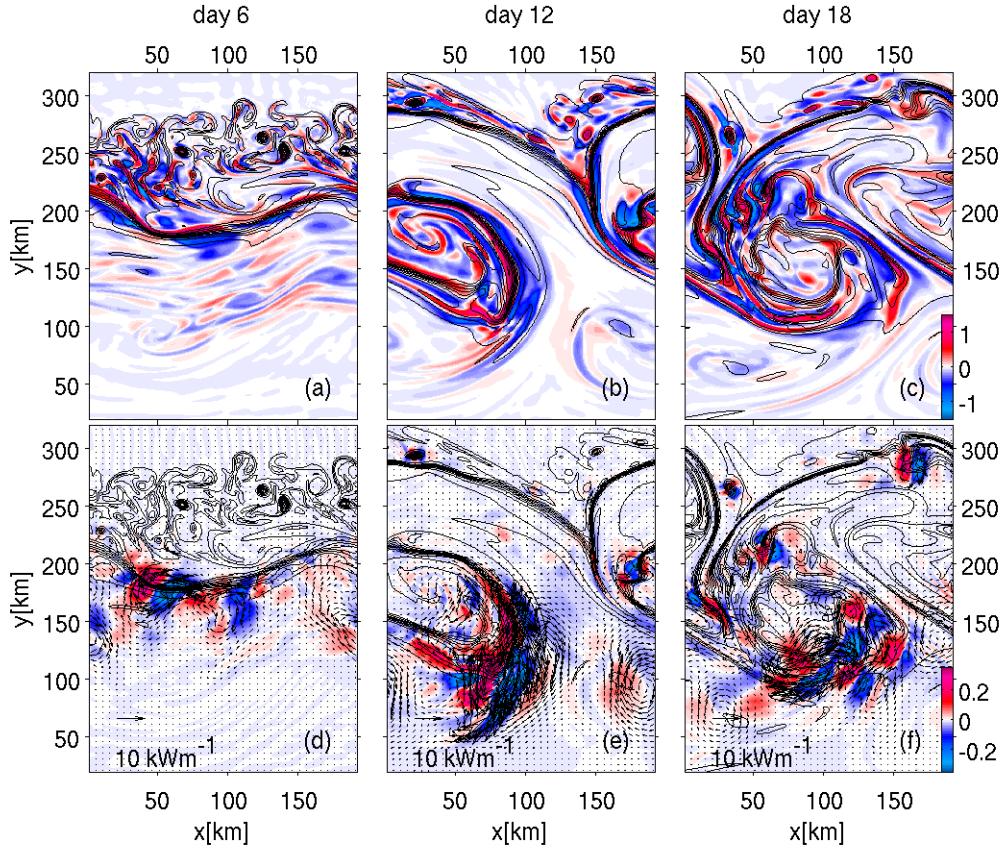


*Figure 3: Top Row: Plan views of the relative vorticity (normalized by f) at three different times during the development of a frontal meander. Lower row: Plan views of near-inertial internal wave (NIW) energy divergence. Red indicates a source (transfer of energy from the balanced flow to the NIW field). Blue indicates a loss of energy from NIW to dissipation. Most of the NIW energy is generated and dissipated in the vicinity of the front and is linked to the meander evolution.*

4

**REFERENCES**

Eady, E.T., 1949. Long waves and cyclone waves. Tellus 1, 33–52

Mahadevan A. and A. Tandon, 2006, An analysis of mechanisms for sub-mesoscale vertical motion at fronts, *Ocean Modelling*, 14 (3-4), 241-256.

Mahadevan, A., 2006, Modeling vertical motion at ocean fronts: Are nonhydrostatic effects relevant at submesoscales?, *Ocean Modelling*. 14 (3-4), 222-240.

Mahadevan, A., A. Tandon and R. Ferrari, 2010, Rapid changes in mixed layer stratification driven by submesoscale instabilities and winds, *J. Geophys. Res.,* 115, C03017, doi:10.1029/2008JC005203.

Mahadevan, A., E. D'Asaro, C. Lee and M-J Perry, Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms, 2012, *Science*, 337 (6090), 54-58, DOI:10.1126/science.1218740

Venayagamoorthy, S. K., Stretch, D. D., On the turbulent Prandtl number in homogeneous stably stratified turbulence, 2010, *J. Fluid Mech*. 644, 359369, 2010.

**PUBLICATIONS**

*Current year:*

Nagai, T., A. Tandon, E. Kunze and A. Mahadevan, (Submitted) Spontaneous generation of internal waves by the Kuroshio front.

Ramachandran, S., A. Tandon and A. Mahadevan 2012, Effect of subgrid-scale mixing on the evolution of submesoscale instabilities, *Ocean Modellin*g (Submitted)

Mahadevan, A., E. D'Asaro, C. Lee and M-J Perry, Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms, 2012, *Science*, 337 (6090), 54-58, DOI:10.1126/science.1218740

Nagai, T., A. Tandon, H. Yamazaki, M.J. Doubell and S. Gallager, 2012, Direct observations of microscale turbulence and thermohaline structure in the Kuroshio Front, *J. Geophys. Res.*, 117(C8), C0801

*Previous years:*

Badin, G., A. Tandon and A. Mahadevan, Lateral mixing in the pycnocline by baroclinic mixed layer eddies, 2011, *J. Phys. Oceanogr.,* 41, 2080-2101.

Mahadevan, A., A. Tandon and R. Ferrari, 2010, Rapid changes in mixed layer stratification driven by submesoscale instabilities and winds, *J. Geophys. Res.,* 115, C03017, doi:10.1029/2008JC005203.

Nagai, T., A. Tandon, H. Yamazaki, and M. J. Doubell, 2009, Evidence of enhanced turbulent dissipation in the frontogenetic Kuroshio Front thermocline, *Geophys. Res. Lett.*, 36, L12609, doi:10.1029/2009GL038832.

**Manuscripts in Preparation**
Idealized mixed-layer simulations using multiple turbulence parameterizations, S. Mukherjee, A. Tandon, S. Ramachandran and A. Mahadevan.